CYCLIC BEHAVIOR OF DOUBLE ANGLE BRACING MEMBERS WITH BOLTED CONNECTIONS

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SUMMARY

Seven full-size (12 ft. long) test specimens, made of double angle sections with bolted connections, were subjected to severe cyclic loading. Test specimens were diagonally mounted in a test frame. First few specimens, designed according to current code procedures, failed in very early cycles. The failures occurred at the bolt holes at end connections as well as stitches. Study of the failure of these specimens led to new design criteria for double angle bracing members with bolted connections. These new criteria and procedures were employed in the design of later specimens. Tests of these specimens showed much improved cyclic behavior.

INTRODUCTION

Behavior of steel frames in seismic environment has been studied by a number of investigators in recent years. The studies have indicated that braced frames are quite efficient in resisting earthquake induced lateral forces. The behavior of braced frames strongly depends on the behavior of bracing members and connections. Double angle bracing members with bolted connections are widely used in steel structures. The object of this study was to investigate the behavior of double angle bracing members subjected to severe cyclic loading normally expected during destructive earthquakes. Full size test specimens were designed according to current (1982) code procedures and tested. Premature failure of some specimens signified the importance of design and detailing of connections. Improved design procedures were formulated to increase the ductility and energy dissipation capability of the bracing members. Tests of specimens, by these procedures, indicated significant improvement.

EXPERIMENTAL PROGRAM

Seven full-size test specimens were subjected to quasi-static cyclic loading. Test specimens are representative of double angle diagonal bracing members used in steel braced frames. The quasi-static cyclic loading was designed to simulate effects of strong earthquakes.

Test Specimens

Details of one of the test specimens are shown in Figure 1. Similar details for all test specimens can be found in Reference (1). Properties of all

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test specimens are given in Table 1. Test specimens consist of two unequal leg angles of hot rolled ASTM-A36 steel. The angles were connected to the end gusset plates and stitched together by 7/8" (22 mm) diameter ASTM-A325 bolts. Connections were designed according to current AISC Specification (Ref. 3).

Test Set-up

Figure 2 shows the test set-up. It consists of a four hinge frame, a support frame, a hydraulic actuator and data aquisition systems. The capacity of the actuator is 250 kips (1.1 MN). The actuator applies a horizontal cyclic force to the upper beam of four-hinge frame causing diagonally mounted specimens to experience severe push-pull deformations.

Deformation History

Similar deformation history was applied to all test specimens. In some cases, due to limitations of test set-up, minor deviations were made. These deviations had no significant effect on the cyclic behavior. Figure 3 shows loading history for specimen AB1 along with a history of major events which took place during the test. Similar plots for other test specimens can be found in Reference 1.

RESULTS AND DESIGN RECOMMENDATIONS

Cyclic Behavior

Specimens having short legs of angles back-to-back buckled in plane of the frame (vertical plane), Figure 4, whereas, specimens having long legs back-to-back buckled out of plane of the frame, Figure 5. Hysteresis loops (axial force - axial deformation curves) were recorded during the tests for all test specimens. Figure 6 shows hysteresis loops for specimen AB1.

In all specimens buckling load decreased significantly from first to the second cycle and continued to decrease gradually during later cycles. Specimens with bearing bolts (no friction) showed significant and ever-increasing slippage. In addition, some of these specimens showed single angle buckling which was attributed to slippage of bolts.

Effective Length Factor

The deformed shape of test specimens at the instant of buckling could be approximated by the elastic buckling curve. Deformed shape of in-plane buckling specimens was resembled by a complete cosine curve and effective length factor of 0.5 is suggested for these members. On the other hand the deformed shape of out-of-plane buckling specimens was nearly a half sine curve resulting in effective length factor of approximately 1.0.

Local Buckling

In-plane buckling specimens showed severe local buckling in their back-to-back legs at plastic hinge locations. Out-of-plane buckling specimen AB2 showed severe buckling in outstanding leg on concave side of the buckled member. Other out-of-plane buckling specimens showed minor local buckling at midspan.

Gusset Plate

In specimen AB7 gusset plates did not show any significant yielding. This specimen buckled in the plane of gusset plates. However, in the other in-plane buckling specimens (AB1, AB3, AB5), which did not have friction bolts, some yielding occurred in gusset plates. The yielding was attributed to single angle buckling which occurred in these specimens. In specimens AB2, AB4, and AB6, which buckled out-of-plane, end plastic hinges formed in gusset plates in the space just beyond the end of the angles, Figure 7. As a result of study of welded specimens (reported in Ref. 2) it was known that a length of gusset plate equal to at least twice the thickness of gusset plate should be provided for plastic hinge formation. This criterion was followed in design of out-of-plane buckling bolted specimens. As a result, despite formation of plastic hinge in gusset plate and severe yielding, no fracture occurred in gusset plates of these specimens.

Stitches

Specimen AB3 had one stitch at midspan as was required by AISC Specification (Ref. 3). The specimens could only survive 8 cycles of deformation and fractured through bolt hole at midspan, Figure 8. Specimen AB5 was fabricated similar to AB3 with the only difference that it had 2 stitches at 1/3 points. This specimen lasted 16 cycles of deformation. The analysis and comparison of the behavior of these two specimens clearly indicated negative effect of stitch at midspan in in-plane buckling members.

Connection of Angles to Gusset-Plates

In out-of-plane buckling specimens, due to formation of plastic hinge outside the connection area in gusset plate, no significant yielding occurred in this region. In in-plane buckling specimen AB1 end plastic hinges formed in the net area of the first bolt. The net area fractured during the sixth cycle. In the remaining in-plane buckling specimens net area was reinforced by welding a plate on the back-to-back leg of angles, Figure 9. The detailed criterion for the reinforcement is given in Reference 1. The major aim of reinforcement was to force plastic hinges to form in gross area instead of net area. Behavior of connections in reinforced specimens was quite satisfactory.

CONCLUSIONS

Based on the experimental and analytical study presented in this paper and Reference 1, the following conclusions and design recommendations are drawn:

1. Double-angle bracing members with bolted connections designed according to current (1982) procedures and specifications may not have sufficient ductility to survive strong earthquakes.

2. For practical design purposes it is suggested that effective length factor be taken equal to 1.0 for out-of-plane buckling specimens and 0.5 for in-plane buckling specimens.

3. Bolted connections should be designed to behave as no-slip type connections. Slippage of bolts may result in single angle buckling causing significant decrease in strength and stiffness of the member.

4. Local buckling occurs at location of plastic hinges. It is suggested that b/t ratio of the legs not to exceed the limits permitted in Part 2 of AISC specification (Ref. 3).

5. In in-plane buckling specimens gusset plates remained almost elastic. In out-of-plane buckling bracing members an adequate free length of gusset plate beyond the angles is necessary to prevent premature fracture in the gussets.

6. Bolted stitches should be avoided at midspan where plastic hinge forms especially for in-plane buckling bracing members.

7. Net section at first bolt hole in connections of in-plane buckling specimens fractures in early cycles. It can be reinforced such that plastic hinge forms in gross section of the angles.

8. Buckling strength of bracing members decreases significantly from first to the second cycle and continues to decrease during following cycles, although at a much reduced rate.

ACKNOWLEDGEMENTS

The research presented in this paper was sponsored by American Iron and Steel Institute (Project 301A). The authors are thankful to Mr. Walter H. Fleischer, Mr. Albert C. Kuentz and other members of the task force for the encouragement they provided. The conclusions and opinions expressed in this paper are those of the authors and do not necessarily represent the views of the sponsor.

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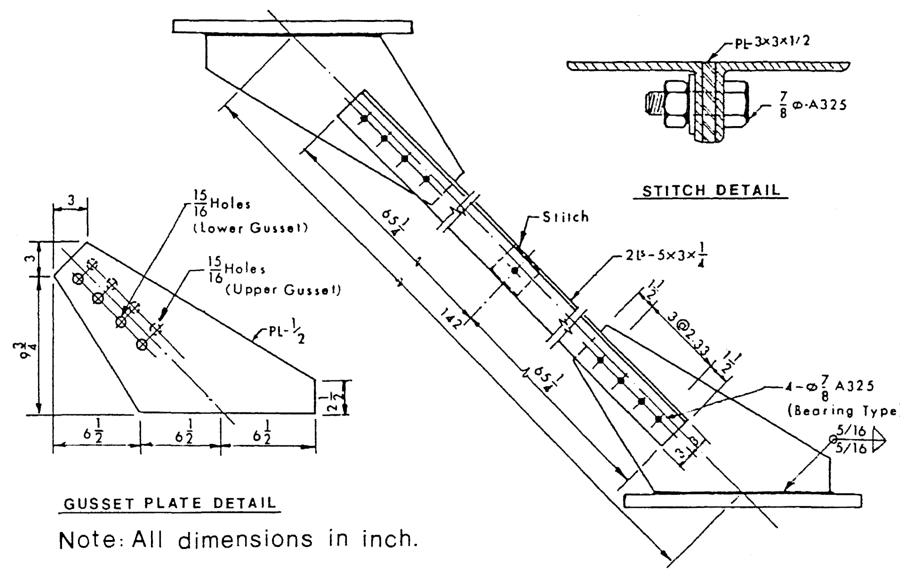

Figure 1 Test Specimen AB1

Table 1 Properties of Test Specimens

Test Spec.	Section (in x in x in) (mm x mm x mm)	A (in^2) (mm^2)	$\frac{K_x L}{r_x}$	$\frac{K_y L^*}{r_y}$	$\frac{b}{t}$	$\frac{b}{t}$	Type of Fastener	Number of Stitches	Number of Cycles to Failure
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
IN-PLANE BUCKLING SPECIMENS:									
AB1	2L-5x3x1/4 (2L-127x76x6.4)	3.88 (2500)	83	57	12	20	Bearing Bolts	1	8
AB3	2L-4x3x3/8 (2L-102x76x9.5)	4.97 (3210)	81	72	8	10.6	Bearing Bolts	1	8
AB5	2L-4x3.3/8 (2L-102x76x9.5)	4.97 (3210)	81	72	8	10.6	Bearing Bolts	2	16
AB7	2L-4x3x3/8 (2L-102x76x9.5)	4.97 (3210)	81	69	8	10.6	Friction Bolts	2	14
OUT-OF-PLANE BUCKLING SPECIMENS:									
AB2	2L-5x3x1/4 (2L-127x76x6.4)	3.88 (2500)	44	114	20	12	Bearing Bolts	1	10
AB4	2L-3x2x1/2 (2L-76x51x12.7)	4.50 (2900)	77	143	6	4	Bearing Bolts	2	21
AB6	2L-3x2x1/2 (2L-76x51x12.7)	4.50 (2900)	77	143	6	4	Friction Bolts	2	19

* Length of all bracing members = 142 in. (3607 mm)

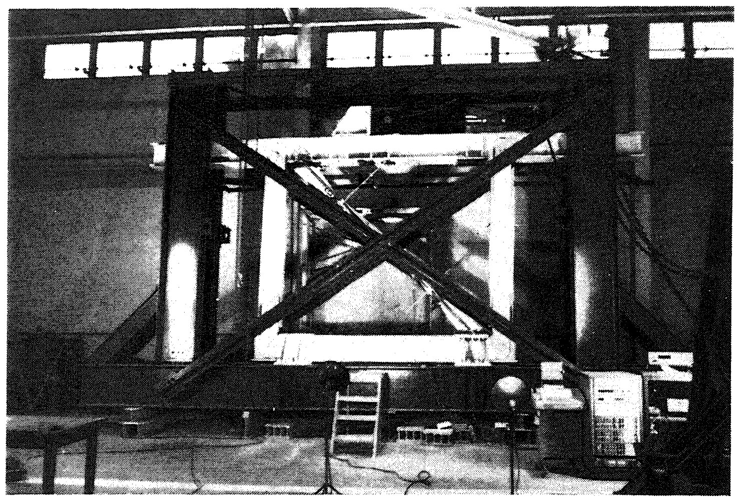

Figure 2 Test Set-Up

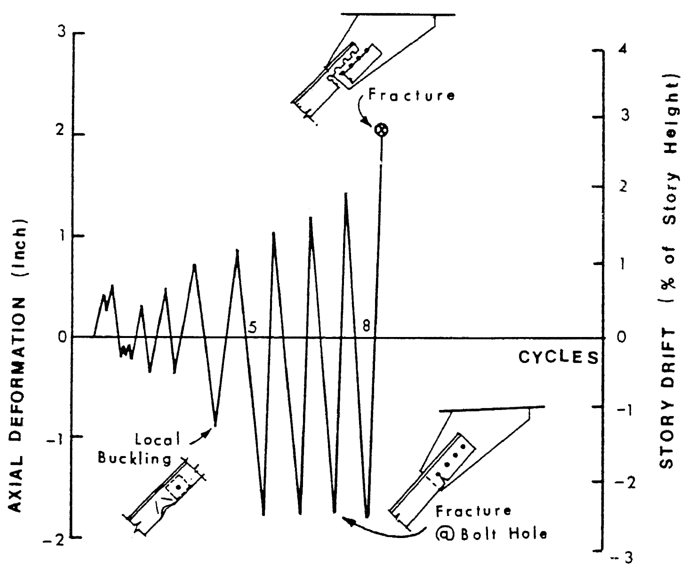

Figure 3 Cyclic Deformation History of Specimens AB1

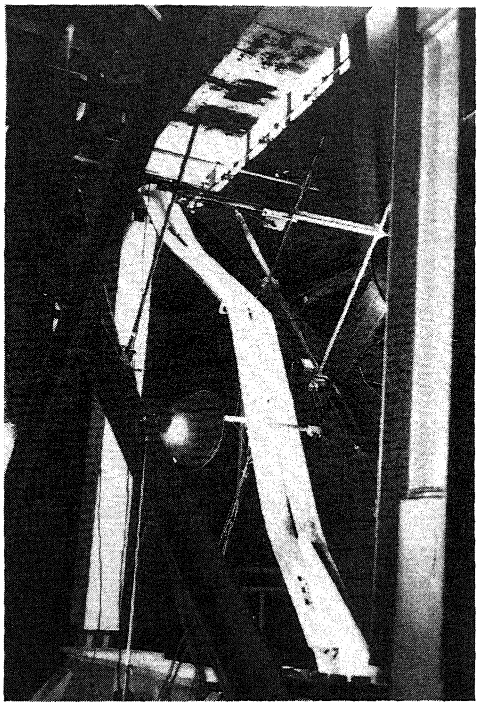

Figure 4 In-Plane Buckling Specimen

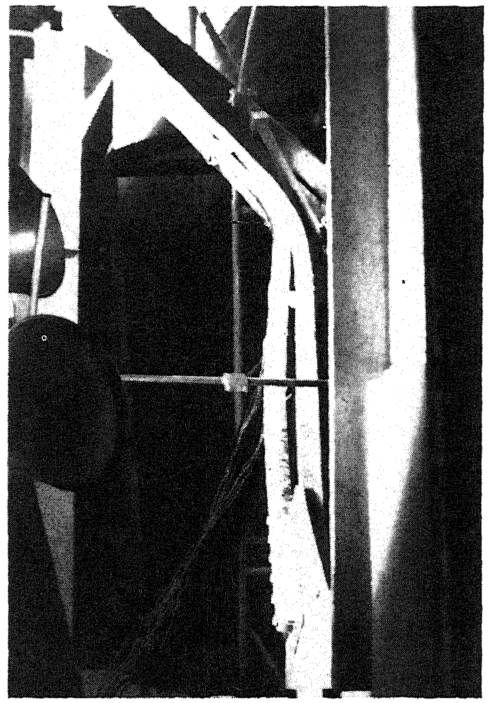

Figure 5 Out-of-Plane Buckling Specimen

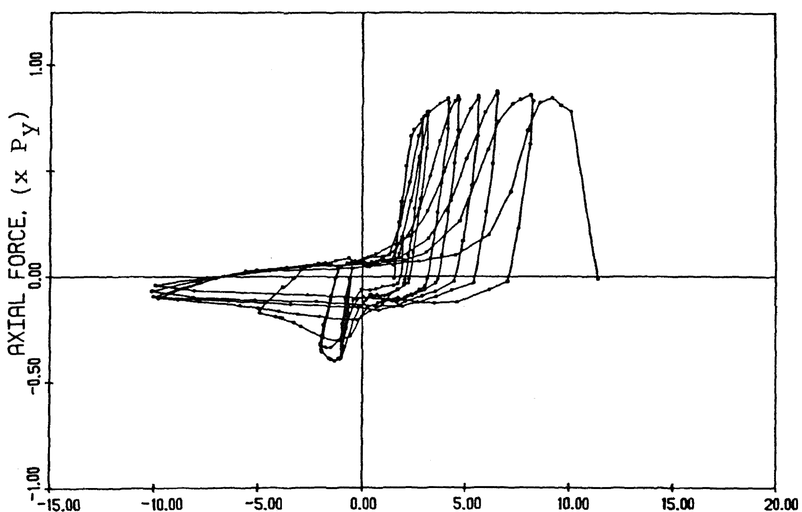

Figure 6 Experimental Hysteresis Loops for Specimen AB1

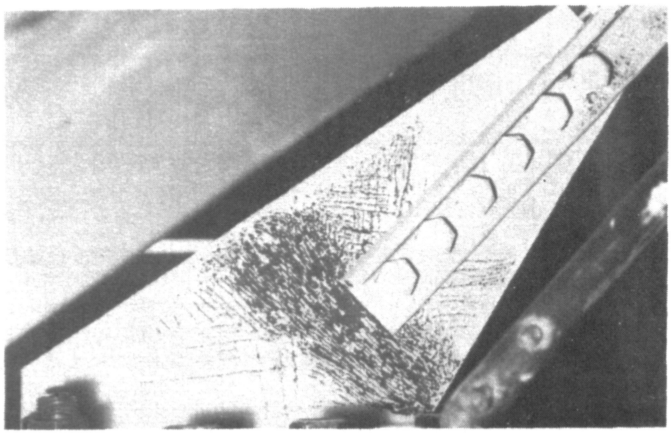

Figure 7 Typical Plastic Hinge in Gusset Plates of Out-of-Plane Buckling Specimens

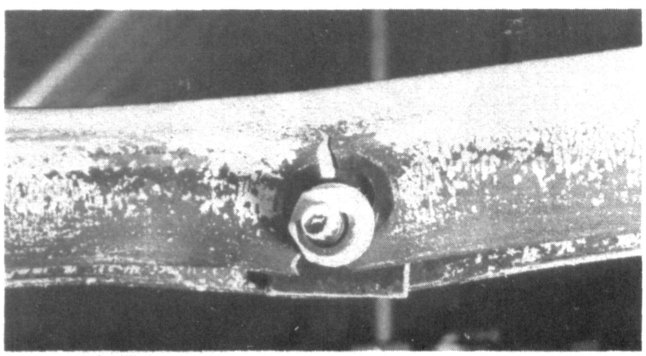

Figure 8 Fracture at Location of Stitch at Midspan in In-Plane Buckling Specimen AB3

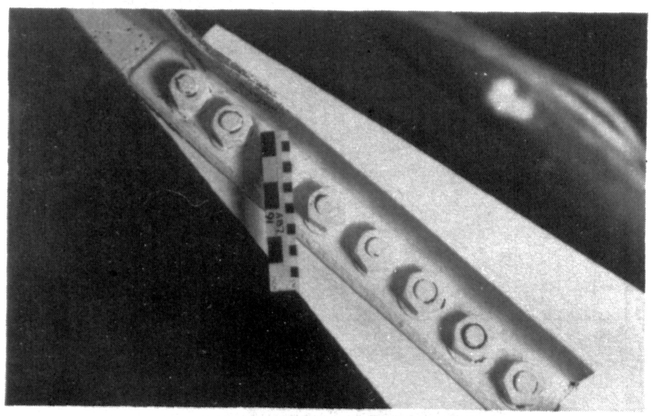

Figure 9 Reinforcement of Net Area in Speciman AB7